

Hot-Dip Galvanizing of Steel Structures

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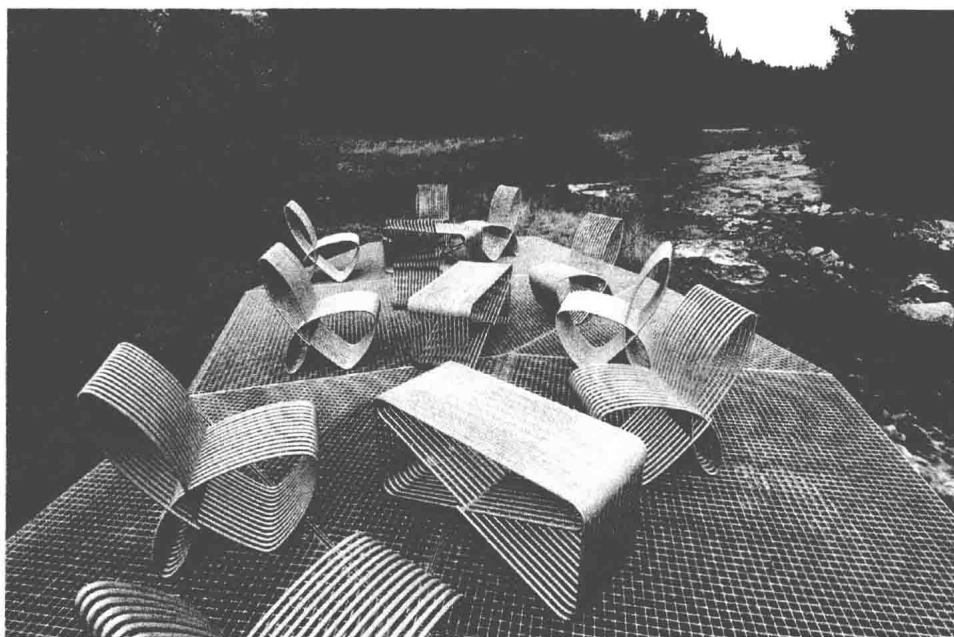


Figure 1 “Living Room in a Landscape [1].”

Preface

The authors were compelled to write this monograph because, although many publications exist on the production of hot-dip galvanized coatings, there are few that provide a comprehensive overview of information about batch hot-dip galvanizing technology that is useful not only for galvanizing plant personnel but also for users of this anti-corrosion protection method for steel.

The contents of this book expand the state of knowledge in the hot-dip galvanizing field using the latest research results that are related to hot-dip galvanizing technology, mechanisms of formation of zinc-based alloy coatings and their accompanying phenomena, and last, but not least, the integrity of hot-dip galvanized steel structures.

The book offers a summary of practical findings about the batch hot-dip galvanizing process. The text also partly deals with the issue of steel corrosion and the principle of zinc-based anti-corrosion protection and provides a brief overview of the most frequently used zinc coating methods. The publication mainly focuses on the technology of applying galvanized coatings in commercial galvanizing plants. In its clearly arranged chapters it describes the principles of designing and producing parts to be hot-dip galvanized, the usual surface pre-treatment processes, the metallurgy of formation of alloy coatings, including their morphological variations, and coating defects as well as repair methods in a detailed way. The final chapters concentrate of the service life of zinc coatings, the European standards, and related legislation with an emphasis on environmental aspects of hot-dip galvanizing.

In this richly illustrated book, the authors have drawn mainly upon the latest global scientific research in the field as well as their own broad experience and numerous experiments conducted to supplement, extend, and verify the conclusions. They hereby want to offer personnel of commercial galvanizing plants a suitable guide that will help them find their way in the field of hot-dip galvanizing as well as related areas. The guide may also provide useful information to other interested people — from students in specialist schools and universities to investors, designers, and manufacturers of zinc-coated parts, corrosion engineers, or surface finishing inspectors.

Some texts cited in the original (2014) Czech language edition have been supplemented and modified for this English language edition.

The original book was reviewed by Viktor Kreibich, Head of the Institute of Engineering Technology on the Faculty of Mechanical Engineering of the Czech Technical University in Prague, and this English translation has been assisted by Murray Cook, Executive Director of European General Galvanizers Association.

The authors thank the reviewers for their constructive comments that contributed to the achievement of the required professional standard of the published work and also thank the authors of the adopted expert articles that supplement the original texts in the required scope.

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Introduction

The method of zinc coating of ferrous metal items by dipping in molten zinc to protect them from corrosion was first officially demonstrated by the French physician Paul Jacques Malouin in 1742 (Figure I.1) [2]. In 1799, Alessandro Volta (Figure I.3) [3] contributed to knowledge of the principle of cathodic protection of iron from corrosion by discovering the galvanic cell. He derived its name from the Italian physician Luigi Galvani (Figure I.2) [4], who observed the effects of electric current and described them in 1791 in his Treatise on Electric Forces. The principle of cathodic protection of 1829 was explained by Michael Faraday (Figure I.4) [5] through an experiment with zinc and iron nails immersed in salt water.

It took nearly a hundred years from the experiments conducted by Malouin for the French chemist Stanislas Sorel [6] to file a patent for galvanic protection of iron from corrosion by application of zinc coating by immersion of a chemically pre-treated zinc object in molten zinc. The patent was filed in 1837 and he called his method galvanizing. Shortly after that, around 1840, the first factories were established in France, Great Britain, and Germany where iron objects were industrially coated with zinc (Figure I.5).



Figure I.1 Paul J. Malouin [2].



Figure I.2 L. Galvani [3].



Figure I.3 A. Volta [4].



Figure I.4 M. Faraday [5].

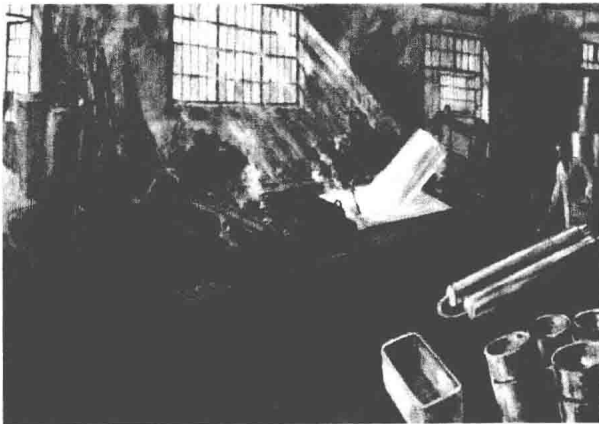


Figure I.5 From the history of hot-dip galvanizing [7].

1.1 Zinc

Zinc is a low melting point, transition metal of the twelfth group of the periodic table of elements. It has a silverish blue and white color with distinctive gloss. It has a hexagonal crystal structure with the tightest arrangement (Figure I.7) and it exhibits considerable anisotropy. At normal temperatures it is tough but at slightly elevated temperatures above 100°C it is very easy to form. At low temperatures it becomes brittle. It exhibits very low strength and hardness. In Earth's crust and sea water, where it is only found in the form of compounds, it is present in a relatively high concentration. The principal raw materials for its production are sulfide (Figure I.6) and oxide ores. From there it is isolated by roasting of enriched ore in



Figure I.6 Zinc ore sphalerite.

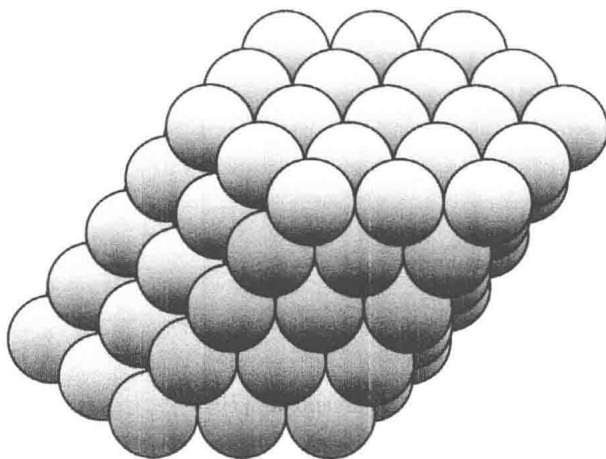


Figure I.7 Crystalline structure of zinc.

multiple-hearth or fluid smelters. Roasted ore containing zinc in oxide form is subsequently agglomerated and distilled or, through metallurgical processes, it is first transformed to the sulphate form by leaching, from which it is then separated by an electrolyte.

Pure (industrially produced) zinc quickly oxidizes when exposed to the air and is prone to corrosion. Under favorable atmospheric conditions it becomes covered by a consistent layer of insoluble zinc carbonate that is highly stable.

As a trace element, zinc is present in living organisms and in all parts of the human body (in organs, tissues, and bones). It is essential for organisms, especially for their growth and for reinforcement of the immune system. Zinc is non-toxic. Organisms ingest it together with food and excrete any excess quantities. It is also an essential raw material for the pharmaceutical industry.

Its very good casting properties are important in industrial uses; it is used to produce castings of complex shapes. Zinc also exhibits good alloying characteristics; it combines well with other metals. It is an important alloying metal for the production of brass. Zinc oxide is used for the production of zinc white and a considerable share of its production is consumed as a filler used in the rubber-making industry.

An important field of industrial use of zinc is the surface finishing of materials. Zinc coatings provide highly efficient and durable protection from corrosion for steel structures and components. The highest volume of zinc production is used for the corrosion protection of iron and steel. Table I.1 below presents an overview of zinc's characteristics.

Table I.1 Overview of zinc characteristics

Zinc		
chemical symbol	Zn	
atomic number	30	
atomic weight	65.37	
characteristic group	transition metals	
valence	2	
color shade	silverish bluish white, lustrous	
crystalline structure	hexagonal (with closest packing)	
density ρ_{20}	7140	[kg.m ⁻³]
melting temperature t_0	419.5	[°C]
boiling temperature t_1	907	[°C]
thermal expansion coefficient α_{20}	29.10 ⁻⁶	[K ⁻¹]
specific latent heat of melting l_1	102	[kJ · kg ⁻¹]
thermal conductivity λ_{20}	109	[W · m ⁻¹ · K ⁻¹]
specific thermal capacity C	385	[J · kg ⁻¹ · K ⁻¹]
tensile elasticity modulus E	100.10 ³	[MPa]
torsion elasticity modulus E	40.10 ³	[MPa]
tensile strength σ_t	120	[MPa]
ductility ψ	60	[%]

(Continued)

Table I.1 (Continued)

hardness	72	[HB]
electrical conductivity	$16,6 \cdot 10^6$	$[S \cdot m^{-1}]$
specific electrical resistivity ρ	59	$[n\Omega \cdot m]$
electrode potential	-0.76	[V]
magnetic properties	diamagnetic	

I.2 Steel corrosion and corrosion protection

In general, corrosion is a very complex process. An understanding of processes and phenomena related to corrosion protection by zinc coatings and of the basic principles must be taken from the current state of knowledge of these aspects as described in the relevant specialized literature (e.g., [8,9]). To provide some guidance on these topics the following explanations give only basic information that is dealt with in more detail by other sources.

I.3 Steel corrosion

Corrosion of metals generally means their undesired, spontaneous, gradual, and irreversible destruction caused by physical-chemical or chemical action of the environment or by biological influences [10,11]. Steel corrosion (Figure I.8) is disruption of the metal due to its electrochemical or chemical reaction with a corrosive environment.

For chemical corrosion of metals (Figure I.9) the reaction occurs in electrically non-conductive, generally gaseous environments. On contact with metal the gas is first dissociated into ions that adsorb on the metal surface (Figure I.9A) and subsequently, due to their chemical reaction with the metal, corrosion products are generated that cover the substrate (Figure I.9B). The corrosion products of chemical corrosion are produced by a direct chemical reaction between the metal and the environment without participation of an electrolyte. A typical example of chemical corrosion is formation of scale during heat processing of scale. During chemical corrosion of steel, oxidation of the metal and reduction of the oxidation component occur at the same time.

From the point of view of the principles and technology of hot-dip zinc coating, it is important to know that steel corrosion is also caused by liquid metals. This is a special case of chemical corrosion where the structural metal does not oxidize but either dissolves in liquid metal or alloy phases are formed that lead to a loss of coherence of the structural metal [9].

Electrochemical reaction in a corrosion cell goes on in the presence of an electrolyte when ionization of the metal (release of cation) and reduction of the

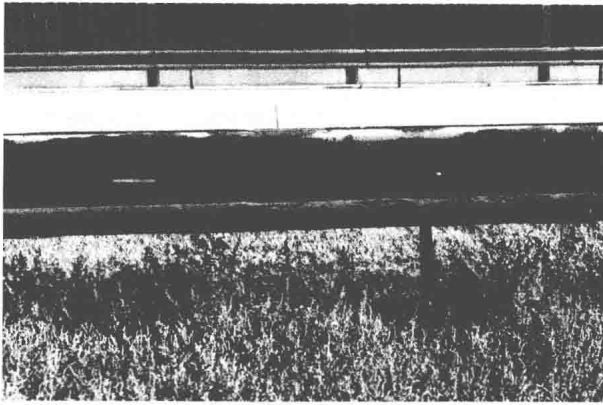


Figure I.8 Steel attacked by electrochemical corrosion.

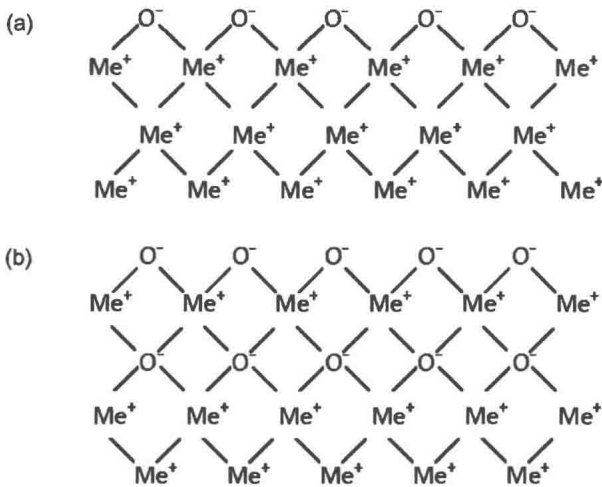


Figure I.9 Principle of chemical corrosion of metals.

oxidation component of the corrosion environment are not in mutual agreement and their rate depends on the electrode (electrochemical) potential of the metal. Corrosion rate is the quantity of metal converted per unit time to corrosion products related to a unit area [12].

The main cause of corrosion of steel exposed to the atmospheric environment is the air humidity, which is a condition for electrolyte formation. Its corrosivity depends on the type of polluting and other substances in the atmosphere and on their concentration. Air pollution by sulphides or chlorides plays an important role. In the industrial environment a determinant of ambient corrosivity is an increased concentration of sulfur dioxide, which is mainly the product of fossil fuel combustion. Chlorides may result from increased salinity of the atmosphere in seaside environments, but an important source is also salt spread on roads.

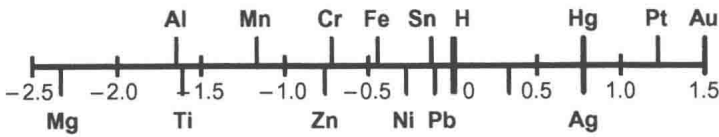


Figure I.10 Electrode potentials of selected metals in salt brine at 20°C [9].

A cause of electrochemical corrosion may consist of an electrically conductive connection between two metals with different electrode potentials in an electrolyte and/or the creation of a concentration cell in a non-homogeneous corrosive environment, e.g., due to variable access of atmospheric oxygen to the steel surface (the aggressiveness of the solution increases in places with limited oxygen access) [8].

Corrosion resistance of structural steel in the atmospheric environment and in water and soil is generally low. Steel is very quickly subject to corrosion in acidic solutions. Conversely, it resists corrosion relatively well in diluted alkaline solutions.

It is important to note that, in a bimetallic cell, it is always the metal representing the anode that corrodes as oxidation is the characteristic for the anode. The cathode is subject to reduction and the metal of the cathode does not corrode. At the same time there is a rule that the metal in the pair that has a lower electrode potential in the particular environment becomes the anode. This metal corrodes first while the cathode metal (with a higher electrode potential value) passes into the immune state.

Figure I.10 shows a list of electrode potentials (redox potentials) of some selected metals from the galvanic series in a diluted aqueous solution of NaCl at 20°C.

I.4 Anti-corrosion protection of steel using zinc

The way in which zinc protects steel from corrosion [13] results from its favorable physical and chemical characteristics, which are very suitable for this purpose (see also Chapter 8):

- A. In an electrically conductive connection with iron, zinc behaves as a sacrificial anode under suitable conditions in most normal environments, i.e., the anode is first attacked by corrosion and ensures that iron is the cathode, which passes into the immune state and thus does not corrode.
- B. A significant feature of zinc is that when it is deposited on the surface of ferrous metals it can create a highly resistant and adherent metallic barrier with the required thickness to separate the coated product from a corrosive environment.
- C. An important aspect is the ability of zinc to be efficiently passivated. If the zinc surface is suitably treated its corrosion rate is decelerated. If a zinc coating is exposed in a dry and sufficiently ventilated environment it becomes covered by a consistent (continuous) layer of corrosion products with high mechanical and mechanical resistance (patina), which decelerates its corrosion in normal atmospheres.